Report for 2005CA124B: Estuarine Landscape Modeling of Suisun Bay

Publications

- Articles in Refereed Scientific Journals:
  - Ganju, N.K., and D.H. Schoellhamer, in press, Annual sediment flux estimates in a tidal strait using surrogate measurements, Estuarine, Coastal and Shelf Science.
  - McKee, L., N.K. Ganju, and D.H. Schoellhamer, 2006, Estimates of suspended sediment entering San Francisco Bay from the Sacramento and San Joaquin Delta, San Francisco Bay, California, Journal of Hydrology, 323, p. 335-352.
- Conference Proceedings:
  - Ganju, N.K., and D.H. Schoellhamer, Lateral displacement of the estuarine turbidity maximum in a tidal strait: submitted for Proceedings of the INTERCOH2005 conference, Saga, Japan.
  - Schoellhamer, D.H., N.K. Ganju, P.R. Mineart, and M.A. Lionberger, Sensitivity and spin up times of cohesive sediment transport models used to simulate bathymetric change: submitted for Proceedings of the INTERCOH2005 conference, Saga, Japan.

Report Follows

Introduction and Problem Statement

California's delicate balance between water supply and ecosystem preservation is under increasing pressure from a growing population and habitat loss. The locus of many of these issues is San Francisco Bay, where freshwater from the Sacramento/San Joaquin Delta meets saline water from the Pacific Ocean. Suisun Bay is the furthest landward subembayment of San Francisco Bay, and is therefore most responsive to freshwater flow. Water withdrawals from the Delta adversely impact the estuarine ecosystem and habitats. Increasing the quality of habitat in Suisun Bay, however, would decrease the ecosystem stress caused by freshwater flow diversions. Current goals of ecosystem restoration include the creation and maintenance of beneficial wetlands and shallow-water habitat (Goals Project 1999).

Geomorphic evolution of estuarine habitats and landscapes over decadal timescales (>10 years) is sensitive to sediment supply from the watershed as well as estuarine hydrodynamics. Sediment supply to the Bay is an ongoing issue, beginning with the drastic input of sediment during the hydraulic mining period of the late 19th century (Gilbert 1917). Today sediment supply is declining due to reduction of the hydraulic mining sediment pulse, reservoir storage, and land use practices (Wright and Schoellhamer in press). Future climate change, land use practices, and sea level rise are some of the many factors that may alter sediment supply and threaten ecologically beneficial estuarine habitats (Scavia et al. 2002, Pont et al. 2002). Hydrodynamics are directly modulated by the varying morphology of the Bay (and vice-versa), so there is a feedback between hydrodynamics and geomorphology.

Objectives

The specific objectives of the research were as follows:

1. Develop a tidal timescale hydrodynamic/sediment transport model of Suisun Bay based on existing public-domain software.
2. Implement idealized boundary conditions for the seaward boundary of the domain, due to the lack historical data for hindcasting simulations.
3. Calibrate and validate the complete model with reference to sediment flux data at the landward and seaward boundaries of Suisun Bay from 1997-1998 and 2002-2004 (McKee et al. 2006; Ganju and Schoellhamer in press).
4. Evaluate the accuracy of a time-stepping procedure which simulates hydrologic seasons as two-week periods, and extrapolates the results for the entire water year.
5. Apply the idealized boundary conditions and time-stepping procedure for hindcasting simulations based on the historical geomorphic data from Cappiella et al. (1999).

Methods

Site description

Our study area is Suisun Bay, the most landward subembayment of northern San Francisco Bay. The Sacramento and San Joaquin Rivers deliver freshwater to Suisun Bay, primarily during the winter rainy season and during the spring snowmelt and reservoir releases. Precipitation is negligible during late spring and summer. Suisun Bay is a partially mixed estuary that has extensive areas of shallow water that are less than 2 m deep at mean lower-low water. Shallow estuarine environments such as Suisun Bay are ecologically significant because a large fraction of the biota depends on these areas for shelter and nourishment (Cloern et al. 1985, Caffrey et al. 1998). Wetlands, which usually form on shallow fringes of the Bay, provide habitat for species and communities not found elsewhere within the Bay (Goals Project 1999). Channels in Suisun Bay are about 9-11 m deep. Carquinez Strait is a narrow channel about 18 m deep that connects Suisun Bay to San Pablo Bay, to the rest of San Francisco Bay, and to the Pacific Ocean. Tides are mixed diurnal and semidiurnal and the tidal range varies from about 0.6 m during the weakest neap tides to 1.8 m during the strongest spring tides. Freshwater inflow typically first encounters saltwater in the lower rivers, Suisun Bay, and Carquinez Strait. The salinity range in this area is about 0-25 and depends on freshwater inflow.

Suspended and bed sediment in Suisun Bay is predominately fine and cohesive, except for sandy bed sediment in some of the deeper channels (Conomos and Peterson 1977). The typical suspended-sediment concentration (SSC) range in northern San Francisco Bay is about 10-300 mg/L and sometimes up to about 1,000 mg/L in an estuarine turbidity maximum (ETM). In Suisun Bay, ETMs are located near sills and sometimes near a salinity of 2, depending on tidal phase and the spring/neap tidal cycle (Schoellhamer and Burau 1998, Schoellhamer 2001a). Accumulations of suspended sediment, nutrients, phytoplankton, zooplankton, larvae, and juvenile fish are found in ETMs (Peterson and others 1975, Arthur and Ball 1979, Kimmerer 1992, Jassby and Powell 1994, Schoellhamer and Burau 1998). The location of a bottom salinity of 2 is used as a habitat indicator to regulate freshwater flow to the Bay because it is believed to be an easily measured indicator of the location of the ETM and a salinity preferred by many estuarine species (Jassby et al., 1995).

An annual cycle of sediment delivery and redistribution begins with large influx of sediment during winter (delivery), primarily from the Central Valley (Goodwin and Denton 1991, McKee et al. 2006). Much of this new sediment deposits in San Pablo and Suisun Bays. Stronger westerly winds during spring and summer cause wind-wave resuspension of bottom sediment in these shallow waters and increase SSC (Ruhl and Schoellhamer 2004). The ability of wind to increase SSC is greatest early in the spring, when unconsolidated fine sediments easily can be resuspended. As the fine sediments are winnowed from the bed, however, the remaining sediments become progressively coarser and less erodible (Conomos and Peterson 1977; Krone 1979; Nichols and Thompson 1985; Ruhl and Schoellhamer 2004). Thus, tides and wind redistribute the annual pulse of new sediment throughout the Bay. Since 1850, alterations in the watershed and estuary have changed the bathymetry of Suisun Bay (Cappiella et al. 1999).

Model development

The Regional Oceanic Modeling System (Shchepetkin and McWilliams, 2005) is a public-domain hydrodynamic model with an optional sediment transport module. There are several advantages that ROMS has over other available models: 1) it is free, public-domain software (which is tens of thousands dollars cheaper than most models); 2) it is improved and expanded amongst hundreds of researchers continuously; and 3) it is part of a community-based sediment transport initiative within the U.S. Geological Survey.

ROMS is a split-mode model: the barotropic, depth-integrated equations are solved on a shorter (fast) time step (due to barotropic propagation speed) while the baroclinic terms are solved at a longer (slow) time step. The grid features of ROMS are: an Arakawa "C" grid (Fig. 5), orthogonal curvilinear horizontal coordinates (Fig. 6), and stretched, terrain-following vertical coordinate. Boundary conditions for momentum/tracers on the four edges of the grid can be clamped (fixed), gradient (zero-derivative), radiation (allow disturbances to propagate away), or wall (zero-flux). In all cases, ROMS has adaptive capabilities, in order to switch from active conditions for inward fluxes and passive conditions for outward fluxes. Discretization options for momentum/tracers range from the 2nd order to 4th order (in space). With regards to turbulence, at least four common two-equation closures (k-epsilon, k-kl, k-omega, and gen) can be specified with the generic length scale implementation provided in the model. Sediment transport in the form of both suspended and bed load (Meyer-Peter Muller version) has been implemented in the latest version of ROMS. Further details of the model can be found at http://marine.rutgers.edu/po/index.php?model=roms.

Idealization of landward boundary conditions: flow, salt, sediment

Net freshwater flow into Suisun Bay is a combination of flows through the Sacramento River, San Joaquin River, the ephemeral Yolo Bypass, minor tributaries, and exports by the federal and state water projects. Because these separate inputs and outputs are not explicitly modeled, the net flow is the parameter of interest. The DAYFLOW program (California Department of Water Resources) balances these inputs and outputs, to yield a daily value of flow past Mallard Island. This value is imposed at the landward boundary of the domain. Conceptually, this ignores the within-Delta transfer of water (and therefore sediment). However, the model will be calibrated to fluxes at the Mallard Island cross-section, so actual sediment retention within the Delta system will be accurately represented (though possible sediment exports by the water projects will be ignored). Salinity at the landward boundary is specified as zero. Periods prior to 1929 require construction of daily hydrographs from monthly and yearly data, as daily data were not available. This method is discussed below.

Daily sediment loads past Freeport on the Sacramento River and Vernalis on the San Joaquin River were obtained from the U.S. Geological Survey. For modeling purposes, the suspended-sediment concentration is specified as a boundary condition, therefore the loads are divided by the DAYFLOW value to yield the appropriate landward boundary SSC. All boundary conditions are spread equally across the cells on the landward boundary, both vertically and laterally.

Idealization of seaward boundary conditions: tides, velocities, salt, sediment

Because the final geomorphic model will be used for simulations spanning the 19th and 20th centuries (when detailed data at the seaward boundary were not always available), idealizations are necessary in terms of tidal height, velocity, salinity, and SSC. Tidal harmonics provide an appropriate initial estimate of historic tidal elevations and velocities. A tidal harmonic predictor was developed from current meter deployments in San Francisco Bay (J. Gartner, writ.. comm.). The predictor provides tidal elevations and velocities at the west end of Carquinez Strait, which is the seaward boundary of the modeled domain. While these values are imposed on the seaward boundary of the model, the actual boundary condition is not strictly clamped, and allows the tidal elevation and velocities to adjust to net outflow (from freshwater flow). Nonetheless, meteorological forcings such as wind and barometric pressure are not represented in the tidal record. The tidal elevation and depth-averaged velocity are applied uniformly in a lateral sense at the seaward boundary, while the 3D velocity field is solved with a gradient condition.

For salinity, the method of Warner et al. (2005) can be used, which utilizes a deterministic function based on near-bottom longitudinal salinity profiles. Data from 358 longitudinal cruises between 1969-2005 of the R/V Polaris were processed to determine this relationship. Within the model code, the salinity gradient is calculated as a function of freshwater flow. This salinity gradient is applied on flood tides, at the first interior point of the domain, to calculate the flood tide salinity. This function was shown to work adequately in prior simulations (Ganju and Schoellhamer, 2005).

Sediment boundary conditions are substantially more difficult, as SSC at the seaward boundary responds to freshwater flow, tidal energy, wind-wave resuspension in San Pablo Bay. Schoellhamer (2001b) constructed synthetic SSC time-series as a means of testing spectral analysis routines; these time-series combined fluctuations in SSC due to seasonal variability of winds, spring-neap tidal energy, and tidal advection. Because flood-tide SSC is the parameter of interest, the measured flood-tide SSC at Carquinez Bridge was averaged on a daily basis. The pattern for water years 2002, 2003, and 2004 showed a similar pattern: a seasonal pattern related to wind-wave resuspension was superimposed on a spring-neap pattern that had greatest variability during high freshwater-flow periods and the least variability at the beginning and end of the water year (when sediment input is at a minimum). Therefore two signals were superimposed to recreate a synthetic time-series of SSC: a seasonal wind-wave signal that peaks in the summer, and a spring-neap signal that is a function of tidal energy (obtained from tidal harmonics). The time-series is then modulated by mean yearly SSC and a random fluctuation that is 10% of the SSC value. The mean yearly SSC at sites Car and PSP is linearly related to total sediment input from the watershed during the water year. This relationship suggests that despite significant tidal and atmospheric forcing, the net sediment input does affect baseline and average SSC throughout the Bay.

Calibration to 2002-2004 fluxes

Calibration of the seaward suspended-sediment concentration boundary condition, sediment properties (i.e. bed shear strength, settling velocity, erosion rate), and Delta configuration will be accomplished by simulating hydrodynamics and sediment transport during water years 2002-2004. Landward boundary conditions and the remaining seaward boundary conditions are specified as outlined above. Calibration goals will consist of simulating the correct net flux between Suisun Bay and the Delta (Mallard Island cross-section), and the correct net flux between Suisun Bay and Carquinez Strait (Benicia Bridge cross-section) within the error bounds of the flux measurements of McKee et al. (2006) and Ganju and Schoellhamer (in press).

Validation to 1997-1998 fluxes

Validation of the calibrated model will be accomplished using flux data from water years 1997-1998. This period contains peak freshwater flows that are 5 times greater than the 2002-2004 period, and average yearly cumulative flow is 3 times larger. Therefore we will calibrate to a relatively dry period, and the mechanics of the model will be validated during a much wetter period. This will ensure that the model is not suited to dry periods only. Again, validation will be quantified in reference to simulating the correct net flux between Suisun Bay and the Delta (Mallard Island cross-section), and the correct net flux between Suisun Bay and Carquinez Strait (Benicia Bridge cross-section) within the error bounds of the flux measurements of McKee et al. (2006) and Ganju and Schoellhamer (in press).

Formulation of time-stepping procedure

Analysis of model results suggests that fluxes over selected two-week periods can be extrapolated individually to represent seasonal dynamics accurately. This procedure was tested for all five modeled water years. Four two-week periods were selected to represent 1) fall conditions (low freshwater flow and reduced wind-waves), 2) winter conditions (high freshwater flow with episodic wind-waves), 3) spring conditions (decreasing freshwater flows and increasing wind-waves), and 4) summer conditions (low freshwater flow and steady diurnal wind-waves). The two-week period contains tidal variability due to the 14-day spring-neap cycle, which is critical for sediment transport processes. The model was then run for each two-week period, and the fluxes were extrapolated for the season by weighting the results to account for one-quarter of a year. The bed changes corresponding to the period were also extrapolated to account for one-quarter of a year. The estimated fluxes by this method compare well to the actual fluxes, while the bed change is also modeled accurately.

Principal Findings and Significance

Calibration to 2002-2004 fluxes

Model results compared well with sediment flux estimates as computed by Ganju and Schoellhamer (in press). The seasonal pattern of sediment flux was represented well, with export during high flows and import during the summer low-flow season. The net sediment import for 2002-2004 was estimated at 1.17 Mt/y by Ganju and Schoellhamer (in press), while the model results show a net export of 0.10 Mt/y.

Validation to 1997-1998 fluxes

Model results compared well with sediment flux estimates as computed by Ganju and Schoellhamer (in press). The seasonal pattern of sediment flux was again represented well, with export during high flows and import during the summer low-flow season. The net sediment export for 1997-1998 was estimated at 21.3 Mt/y by Ganju and Schoellhamer (in press), while the model results show a net export of only 1 Mt/y. This discrepancy is largely due to the large predicted export in water year 1998. The model results do not accurately represent the predicted sediment fluxes, though model improvements are being implemented to correct this flaw.

Formulation of time-stepping procedure

Four two-week periods were selected for each water year, and the flux results for those periods were extrapolated to represent the entire year. The average error for all five water years for this procedure was less than 15%. Considering the 85% reduction in computational time, this is an adequate way to increase computational efficiency.

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INFORMATION TRANSFER PROGRAM: Provide a brief description of information transfer activities supported with section 104 and required matching funds during the reporting period.

1. Provide a brief description of the information transfer activity for your project.

   Information transfer has encompassed poster presentations, oral presentations, and seminars at multiple forums. Primary goals were receiving feedback on methods and goals, while informing associated researchers of our intentions and possible opportunities for collaboration. Through these efforts, collaboration has commenced with USGS researchers spanning disciplines (climatology, hydrology, aquatic biology, remote sensing, benthic ecologists, etc.), primarily through the CALFED-funded CASCaDE project.